Using KML and Virtual Globes to Access and Visualize Heterogeneous Datasets and Explore their Relationships along the A-Train Tracks

Aijun Chen[1, 2], Gregory Leptoukh[1], Steven Kempler[1]

[1]Goddard Earth Sciences Data and Information Services Center (GES DISC),
NASA Goddard Space Flight Center, Code 610.2, Greenbelt, MD, 20771, USA
[2]Center for Spatial Information Science and Systems (CSISS), George Mason University,
6301 Ivy Lane, Ste. 620, Greenbelt, MD 20770, USA

Abstract: Keyhole Markup Language (KML), the *de facto* standard for representing, visualizing and transmitting geospatial data on Virtual Globe, lately approved by the Open Geospatial Consortium (OGC), Inc., has been widely used by the Earth Science communities. Most of the popular virtual globe systems, such as Google Earth and Microsoft Virtual Earth support KML format. This new online approach is changing the way in which scientists and the general public interact with three-dimensional geospatial data in a virtual environment. The so-called A-Train, a series of seven U.S. and international Sun-synchronous satellites, flying in tight formation just seconds to minutes apart, across the local afternoon equator, has been producing abundant measurements of vertical profiles of atmospheric parameters. This paper first discusses the key technical points for access to and visualization of three-dimensional Earth science data by using KML and Virtual Globe. Then, the Virtual Globes are taken as a virtual three-dimensional platform to synergize horizontal data and vertical profiles along the A-Train tracks to explore the scientific relationships among multiple physical phenomena. Two kinds of scientific scenarios are investigated: a) The relationships among cloud, aerosol and atmospheric temperature, and b) the relationships among cloud, wind and precipitation. The seamless visualization and synergy of multiple versatile datasets facilitate scientists to easily explore and find critical relationships between some phenomena that would not be easily found otherwise.

Keywords: Synergy of Heterogeneous Datasets, KML, Virtual Globe, A-Train, Vertical Profiles.

1. Introduction

Keyhole Markup Language (KML) is becoming one of the most popular tools for professionals and the general public for expressing, managing, and visualizing geolocation-related digital data on Virtual Globes. It has become both a *de facto* standard and an Open Geospatial Consortium, Inc. (OGC)-approved official standard. KML is an Extensible Markup Language (XML) compatible markup language that both people and computers can read. It was first developed for use with Google Earth. Virtual Globes, such as Google Earth, Microsoft Virtual Earth, and United States National Aeronautics and Space Administration (US NASA) World Wind, are facilitating exploration, overlay, release, and sharing of information on any subjects that have geographical elements. Virtual Globes are changing the way in which scientists and general public interact with the geospatial data in a virtual environment. The most attractive point of Virtual Globes is the ease with which users can zoom into street level from the global, add, manage and share their data in KML format, and find data of interest to others. Therefore, there is hope that all sorts of information on the state of the planet will become available to all with a few moves of the mouse [1].

The NASA A-Train satellite constellation is a series of U.S. and international Sun-synchronous satellites, consisting of seven missions -- three Earth Observing System (EOS) missions, three Earth System Science Pathfinder (ESSP) missions, and one French Centre National d'Etudes Spatiales (CNES) mission, all flying in tight formation across the local afternoon equator just seconds to minutes apart. In order of equator crossing, right now, the A-Train seven missions are Aqua, CloudSat, Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO), Polarization and Anisotropy of Reflectances for Atmospheric Science coupled with Observations from a Lidar (PARASOL), and Aura. The Orbiting Carbon Observatory (OCO) and Glory are another two satellites planned in A-Train constellation, however, the OCO satellite failed on launch on February 24, 2009 and Glory satellite were scheduled to launch in 2010. Formation flying only will not increase the number of observations, it does increase the number of collocated observations. Formation flying also helps to validate observations, and enable coordination and synergy between different observations. Enabling synergy means that more information about the condition of the Earth is obtained from the combined observations than would be possible from the sum of the observations taken independently [2]. Figure 1 illustrates the A-Train satellite constellation.

Figure 1

Figure 1 shows the seven satellites (planned) comprising the "A-Train" sequence of formation-flying satellites. The last satellite (EOS Aura) has a mean equator-crossing time only 23 minutes after the first satellite OCO, which failed on launch in 2009, allowing for near-simultaneous Earth remote sensing observations (Glory, to be launched in 2010). (Photo courtesy of NASA)

NASA Goddard Earth Science Data and Information Service Center (GES DISC) and its cooperators have made great process in providing researchers means to visually explore the A-Train vertical profiles, provide online data access, and distribute datasets derived along the A-Train tracks from the A-Train constellation. Using KML and Virtual Globes further enhances such exploration—data access to and distribution of those heterogeneous datasets with different data structures, data formats, fields of view, and resolution. Using KML and the three dimensional template of Virtual Globes, those datasets can be freely and animatedly visualized using transparent vertical curtains for vertical profiles and horizontal thematic maps for horizontal data. A "curtain" consists of series of images that represents vertical information of physical phenomena in the atmosphere and are vertically displayed on the surface of a Virtual Globe along a track. Further, Virtual Globes provide a good visualization and data integration platform, through which, vertically and horizontally oriented datasets can easily be combined together to fulfill the purpose of NASA's A-Train. Examples are integration and visualization of vertical curtains from CloudSat and CALIPSO, cloud top pressures from the Moderate Resolution Imaging Spectroradiometer (MODIS)/Aqua and Atmospheric Infrared Sounder (AIRS)/Aqua, and cloud pressure from Ozone Monitoring Instrument (OMI)/Aura, which reveal cross instrument data signatures not otherwise easily detected. The capabilities of Virtual Globes, such as zooming, panning, tilting, and rotating, give users opportunities to browse and examine features prior to deciding to acquire data. As soon as data of interest are found, users are able to use other Web-based services, such as File Transfer Protocol (FTP), Hypertext Transfer Protocol (HTTP), Web Map Service (WMS), Open-source Project for a Network Data Access Protocol (OPeNDAP), to access those data from the archive in which raw data reside.

Large volumes of heterogeneous datasets are provided to Earth science users at NASA GES DISC. The following datasets are involved in KML and Virtual Globes: CloudSat, CALIPSO, MODIS/Aqua, AIRS/Aqua, Microwave Limb Sounder (MLS), and Tropical Rainfall Measurement Mission (TRMM). Most of which include five dimensions of information: temporal, spatial (three dimensions), and physical parameters.

Since the 2006 meetings of the Association of American Geographers (AAG) and the American Geophysical Union (AGU), much Earth science related research and applications have involved KML and Virtual Globes. However, most of them dealt with technical aspects of how to visualize the Earth science related data on Google Earth alone [3][4][5][6][7][8][9]. Goodman et al. [10] integrated several kinds of heterogeneous data, including 2D, 3D and ground station data, for using Google Earth to monitor NASA missions in real time. This work is a successful application of integrating, visualizing, and synergizing heterogeneous data on Google Earth for real-time mission monitoring.

2. Access to and Visualization of Heterogeneous Datasets

To facilitate using integrated, publicly available tools and services to access NASA Earth science data, ubiquitous access is first provided by existing services at GES DISC; then, KML-based visualization of vertically and horizontally measured data is designed and implemented. These techniques are the foundation for further synergizing heterogeneous data products on Virtual Globes. Figure 2 illustrates how users access to heterogeneous data products in data archives and visualizing them on Virtual Globes. Users can only view the curtain in images, no actual measurements available from the curtain. But, users can download data products for actual measurements in number value. There are two technical challenges we encountered: a) Ubiquitous access to multi-source datasets and rendering acquired data into images; and b) Rendering vertical profiles on Virtual Globes. We detailed our solutions in following sections.

2.1 Heterogeneous datasets from A-Train and other missions and ubiquitous online access to them

The A-Train satellite constellation has been producing large volumes of heterogeneous atmospheric data from different satellites. Some of them are processed and visually synergized to discover hidden scientific results. The following A-Train mission data have been processed (see the data management layer in Figure 2).

Figure 2

The CloudSat satellite, launched by NASA on April 28, 2006, has been collecting data since June 2, 2006, It records a 3D view of the vertical structure of clouds from the top of the atmosphere to the surface. The radar observations are processed into estimates of water and ice content with 500m vertical resolution [11].

The CALIPSO mission explores the atmosphere and studies the aerosols and thin clouds that play a major role in regulating earth's weather, climate, and air quality. It provides data about the vertical structure of clouds and aerosols that is unavailable from other earth-observing satellites. CALIPSO globally surveys the vertical distribution and optical and physical properties of aerosols and clouds in the atmosphere [12]. On CALIPSO, there are loaded three co-aligned, near-nadir viewing instruments: a 2-wavelength polarization-sensitive lidar, an imaging infrared radiometer, and a high-resolution wide field camera. The lidar profiles provide information on the vertical distribution of aerosols and clouds, cloud particle phase, and classification of aerosol size [13].

AIRS/Aqua and MODIS/Aqua collect vertical profiles of atmospheric temperature, H_2O saturation, and of H_2O vapor. AIRS measurements of the Earth's atmosphere and surface allow scientists to improve weather predictions and observe changes in Earth's climate, Much of the data from MODIS includes 3D features of the land, oceans, and atmosphere, which will improve our understanding of the dynamics of global processes [14]. Both sets of data are processed in two-dimensions and three-dimensions.

OMI/Aura is from the Netherlands Agency for Aerospace Programs, on the EOS Aura mission. It continues satellite measurements of global total ozone trends, maps zone profiles at 36 x 48km, measures key air quality components, for example, NO_2, SO_2, BrO, and aerosol characteristics, and distinguishes between aerosol types such as smoke, dust, and sulfates.

The TRMM has three instruments: the Visible Infrared Scanner (VIRS), the TRMM Microwave Imager (TMI), and Precipitation Radar (PR). The Precipitation Radar provides data on the intensity and distribution of rain, on the rain type, on the storm depth and on the height at which snow melts into rain [15]. Gridded Level 3 data products from those sensors are archived, accessed, processed, visualized, and synergized on Virtual Globes. The products describe the following tropical rainfall-related core physical parameters: rain rate, rain frequency, mean surface rainfall, combined calibrated rainfall, rain rate probability distribution, vertical hydrometeor profiles, cloud liquid water, rain water, cloud ice, and convective/stratiform heating [16].

Most of the data are archived in a system designed and implemented by GES DISC named the Simple, Scalable, Script-based Science Processor Archive (S4PA). S4PA is a simplified data archive architecture for supporting GES DISC users with online access to data. S4PA is already being used operationally and its deployment will be expanded in the future. The S4PA offers ubiquitous access to most of the Earth science data at GES DISC. Data processing system/services, such as the Goddard Interactive Online Visualization ANd aNalysis Infrastructure (Giovanni), WMS, and Web Coverage Service (WCS), access data of interest to the user through the S4PA. The archived data are available via FTP and OPeNDAP.

2.2 Processing and Visualization of heterogeneous datasets on Virtual Globes

Giovanni is an online interactive analysis and visualization tool for exploring most of the Earth science datasets at GES DISC [17]. It provides Web-based interoperable data exploration, statistical analysis of physical phenomena, and downloading of subsets of data of multiple sensors, independent of the original file format. Giovanni version 3 uses service- and workflow-oriented asynchronous architecture [18]. S4PA, as the main system for archiving and serving raw data, makes most of the data ubiquitously available to the Giovanni system. Other standard protocols, such as FTP, OPeNDAP, WMS and WCS, and Grid Analysis and Display System (GrADS) Data Server (GDS) are also available for providing and processing data. Service-oriented architecture (SOA) requires that all data processing and rendering be implemented using standard Web services. Doing so increases the reusability, modularization, standardization, and interoperability of the system components. With this design, system infrastructure and the logic and algorithms of data processing/rendering can be clearly separated. Asynchronicity (means that http server doesn’t need to response to client immediately after received a task from client. The http server can response client after the task finished) guarantees that complex processing can be done without being limited by HTTP time-outs, and that Web services in a process can be run in parallel. Giovanni is an easily used, intrinsically extensible and scalable, high-performance software system [3].

WMS is used to process raw data that are ubiquitously accessible through OPeNDAP. It processes the data and puts out the results in jpg, png, or gif format. Two KMZ (zipped KML file) generators are proposed, designed and implemented as service components and integrated into the SOA-oriented Giovanni system. One generator, the KMZ Generator for Vertical Data (KGV), is for processing vertical profiles; the other, the KMZ Generator for Horizontal Data (KGH) is for processing horizontal data. KGV accepts a vertical image curtain from Giovanni and generates KMZ for users. A vertical image curtain of the data is used to generate the KMZ files by rendering the image in KML format to visualize the data on a Virtual Globe [3]. KGH consists of two separate components. One accepts input from Giovanni and the other accepts input from WMS. KGH processes received images and produces KMZ files to visualize data on a Virtual Globe.

KGV implements automatic acquisition of the vertical image curtain from Giovanni. It collects parameters from users via the Giovanni Web Interface and automatically builds up a parameters file in XML format for the temporal and spatial range selected by the user. For vertical profiles such as those from CloudSat, CALIPSO, and AIRS/Aqua, the user can choose among the available physical parameters (e.g. Radar Reflectivities (dBZ) and Received Echo Powers (REP)) to view. The available physical parameters are the atmospheric temperature from AIRS, MODIS, the European Center for Medium-Range Weather Forecasts (ECMWF) model, and MLS; the H_2O saturation mass mixing ratio and H_2O vapor mass mixing ratio from AIRS/Aqua; relative humidity with respect to ice from MLS; the retrieved dew point temperature profile from MODIS/Aqua; the s pecific humidity profile from the ECMWF model, Cloud/Aerosol Classification (Vertical Feature Mask) from CALIPSO; ice water content and ozone mixing ratio profile from MLS, Cloud scenario, received echo powers, reflectivity (dBZ), cloud ice water content (radar-only) and liquid water content (radar-only) from CloudSat. Those physical parameters reflect different aspects of natural phenomena that scientists are investigating. Scientists can integrate and synergize those physical parameters on Virtual Globes to discover and resolve Earth-related issues. The parameters are input into the Giovanni workflow that fetches appropriate geospatial vertical data from the data archive system from the parameters' file. Then, a series of processing procedures, such as data fetching, stitching, sub-setting, extracting, scaling, and rendering, is used to generate the data image curtain. Figure 3 is an example image curtain of CloudSat data visualized on Google Earth.

Figure 3

KGH operates completely differently from KGV. Horizontal data is processed differently from vertical profiles. First, KGH produces a general KML framework determined by parameters selected by the user. Then, those parameters are used again to form a Giovanni URL request or a WMS URL request that is embedded into the KML framework to form the final KML file. When the user opens the KML file on Virtual Globes, data are requested, processed, and rendered in real time by the Giovanni or WMS server. The advantage of this procedure is that the KML file is very small; it downloads rapidly. However, success in viewing the data on a Virtual Globe depends on the availability of the Giovanni server and data when the KML file is opened on a Virtual Globe. However, KGV generates everything needed to produce the KMZ file and lets the user download it. Later, no matter when the user opens it on Virtual Globes, it works locally; the Giovanni server need not be accessed again. The disadvantage of KGV is that the size of the KMZ file is bigger than the KML file produced by KGH, usually one megabyte for one hour of temporal range of vertical curtain.

3. Synergy of Heterogeneous Datasets and Case Study

KML is the medium and Virtual Globes the venue where KML files synergize to give a unified picture of related physical phenomena. Visualizing data that are measured vertically and horizontally reveals cross-instrument data signatures not otherwise easily detected. Synergizing A-Train with other sensing data on Virtual Globes increases users' abilities to discover, access, manipulate, and analyze A-Train atmospheric data. Vertical and horizontal data can be viewed both transparently and opaquely on Virtual Globes, allowing simultaneous visualizations for efficient exploration of relationships among large volumes of geospatial data. The synergy of heterogeneous datasets is applied to two application scenarios to help reveal scientific issues.

Synergizing geospatial data can be made between: a) vertical data, b) horizontal data, and c) vertical data and horizontal data. All A-Train vertical data can be synergized along the A-Train track, to help scientists explore the relationships and interactions between multiple atmospheric physical phenomena. Horizontal data, such as MODIS/Terra, MODIS/Aqua, and OMI/Aura can be synergized to investigate scientific questions, such as monitoring air quality and ozone. Synergizing vertical data and horizontal data together provides a virtual three-dimensional environment for better observing, comparing, and understanding the atmospheric data. For example, by ingesting meteorological measurements for a given area of interest or event recorded at times closest to the A-Train flyby, and integrating them all into a view of visualization on a Virtual Globe, the effects of temperature, atmospheric pressure, wind speed and direction, and weather conditions can be better understood. In particular, the effects of increasing pressure gradients or changing temperatures on atmospheric components may reveal interesting aspects of the behavior of the total atmosphere. Two application scenarios are given below, corresponding to the a) and c) synergies discussed in this paragraph. In fact, any data whose KML/KMZ are available can be selected for synergizing to try to answer scientific questions.

3.1 Relationship and interaction of cloud, aerosol, atmospheric temperature, and cloud top pressure

Atmospheric vertical profiles and surface strips from the A-Train constellation's CloudSat, CALIPSO, and ARIS/Aqua are integrated and visualized on Google Earth. The vertical profiles describe such vertical characteristics in atmosphere as cloud reflectivity (dBZ) derived from CloudSat, cloud/aerosol classification (vertical feature mask) from CALIPSO, and atmospheric temperature from MODIS/Aqua. Surface strips reflect the cloud top pressure derived from MODIS/Aqua. Using the visualized synergy shown in Figure 4, scientists can discover the relationships and interactions between cloud, aerosols, atmospheric temperature, and cloud top pressure. Aerosols are closely related to cloud formation. Aerosol-cloud interactions are seen as one of the most important single forces that drive climate change [19]. The temperature around the aerosol increases, when water vapor coagulates on the surface of an aerosol particle, then the cloud forms. The vertical distribution of the cloud is closely related to the atmospheric temperature, and the cloud top pressure is related to the vertical characteristics of the cloud. Figure 4 shows that the atmospheric temperature close to the surface is higher, and the top pressure of the cloud close to the surface is lower than the pressure of the cloud far away from the surface. Also, obviously, the atmospheric temperature is missed within the field of full of clouds because of the sensitivity of the MODIS instrument. This convenient virtual synergy amongst different atmospheric parameters allows observation and discovery of more interesting phenomena.

Figure 4

3.2 Relationship and interactions of cloud, wind, and precipitation

Figure 5 shows the synergy of vertical and horizontal geospatial data from CloudSat, TRMM, and QuikSCAT for typhoon Prapiroon on August 2, 2006. The vertical orbit curtain describes the radar reflectivity (dBZ) of cloud vertical structure derived from CloudSat. The horizontal data represent the three-hourly rainfall rate (3B43) from TRMM satellite and wind data from QuikSCAT. On this date, the typhoon was located over the South China Sea. The CloudSat parameter shown is the dBZ reflectivity. The heights of the highest clouds are ~15 km. Substantial convective activity can be seen within the vertical structure of the typhoon. The 3B43 three-hourly TRMM data shows the rainfall rate and QuikSCAT data shows the wind in the area of the typhoon. The synergy clearly shows the relationship and interaction of the typhoon, rainfall, cloud, and wind. The figure shows that the thicker the cloud is, the stronger the wind, and the higher the rain rate. Scientists use such kinds of results to forecast weather and disasters, analyze climate change based on huge volumes of archived historical data, report air quality, and carry out other atmospheric-related scientific research. These results can also help general users comprehend the relationships of rainfall, cloud, and wind.

Figure 5

3.3 Integration and synergy of geospatial data for special events

Virtual Globes can be used as a three dimensional virtual platform to geospatially organize and integrate any geolocation-related data, especially for sudden events, such as hurricanes, earthquakes or bird flu. For example, when a hurricane happens, all data and information related to the area involved can be quickly organized, made into KMZ files, and published on the rescue website. Decision-makers, volunteers, and other involved persons can view the current situation by opening the near real-time KMZ files on Virtual Globes. Past and near real-time data and information about the atmosphere, sea, and rainfall from satellites and ground stations can be integrated for decision-makers. Any available information related to rescue tools, search plans, government agencies, and volunteers can be dynamically and interactively put together for timely rescue and help based on visually and straightforwardly geospatial positions on Virtual Globes [20]. The key points for these kinds of applications are how to acquire and serve real-time data using suitable services. Considering that the image will be reloaded while you open the KMZ files on Virtual Globes every time, using OGC WMS in KML file will help to update/fresh the data on Virtual Globes as only as we update the datasets served to WMS in real time. In fact, we discussed this technology in the paper and used for visualizing Hurricane on Google Earth at GES DISC.

As the issue of global climate change becomes increasingly critical, policy-makers are becoming more concerned about local environmental problems and sudden natural hazards. The method and system introduced here is an additional tool that professionals can use to integrate socio-economic information with geospatial data on the Virtual Globes' environment to assist policy-makers in making better decisions for improving people's lives.

4. Conclusions and Future Work

KML and Virtual Globes are becoming increasingly popular and are facilitating professional research and affecting the daily life of the general public. This paper shows how they can be used to facilitate access to and synergy of heterogeneous atmospheric data at GES DISC for scientific research and discovery. Two-dimensional and three-dimensional heterogeneous data from GES DISC are introduced, visualized, and synergized. A diagram of the system framework illustrates the data storage and archiving component, the data access and processing component, the KMZ generator components and the user interfaces. The system can be used to synergize heterogeneous datasets from different sources. Two kinds of synergy are described and two application cases have been introduced, to show the advantages at GES DISC of synergy. Some examples are available online at http://disc.gsfc.nasa.gov/googleearth.

Through the use of KML, Virtual Globes are now providing a method for visualizing and comparing diverse, simultaneous data from different data sources, revealing new information and knowledge that would otherwise have been hidden, now becomes possible. Future use for scientific research presents both hope and challenges. A promising direction for scientific research is to utilize the Virtual Globes as web browser Plug-ins. This would allow greater integration between online scientific data analysis systems and visualization, and would obviate the need for users to migrate the results to a separate window containing a Virtual Globe. In short, the future of the Web is to be geospatially enabled by default – a 3D virtual platform of our planet, available by default on the Web for use in scientific research and daily life. Now, Virtual Globe provides a platform for geospatially organizing and visualizing geospatial data. However, the challenge had to be faced is, no matter for Virtual Globe or Virtual Globe-based applications, how Virtual Globe and it-based applications become a platform for facilitating the online analysis and synergy of huge volumes of geospatial data.

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Figure 1 the A-Train satellite constellation.

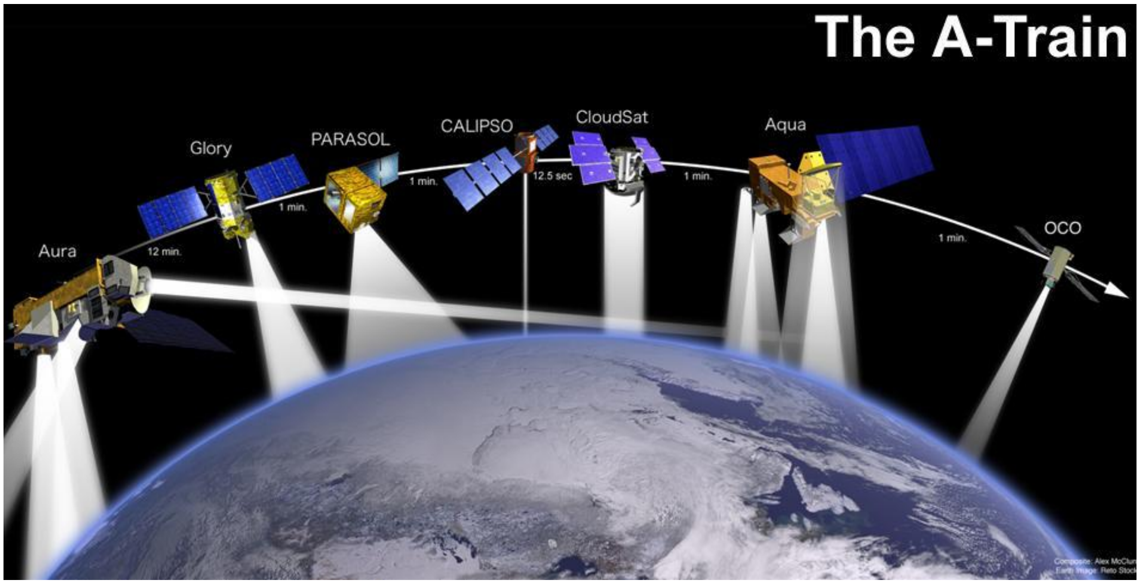
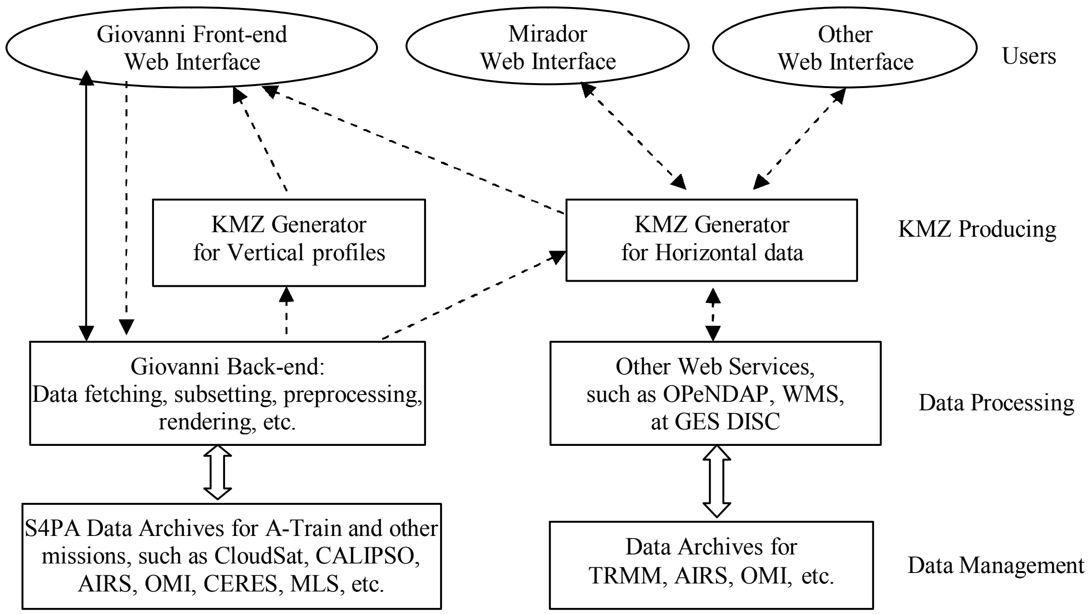


Figure 2. The diagram of access to heterogeneous data products in data archives and visualization of them on Virtual Globes



Legends:

KMZ: Zipped Keyhole Markup Language

OPeNDAP: Open-source Project for a Network Data Access Protocol

WMS: Web Map Service

GES DISC: Goddard Earth Science Data and Information Service Center

S4PA: Simple, Scalable, Script-based Science Processor for Archive

CALIPSO: Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation

AIRS: Atmospheric InfraRed Sounder

OMI: Ozone Monitoring Instrument

CERES: the Clouds and the Earth’s Radiant Energy System

MLS: Microwave Limb Sounder

TRMM: Tropical Rainfall Measurement Mission

Figure 3. an example of the image curtain of CloudSat data visualized in Google Earth

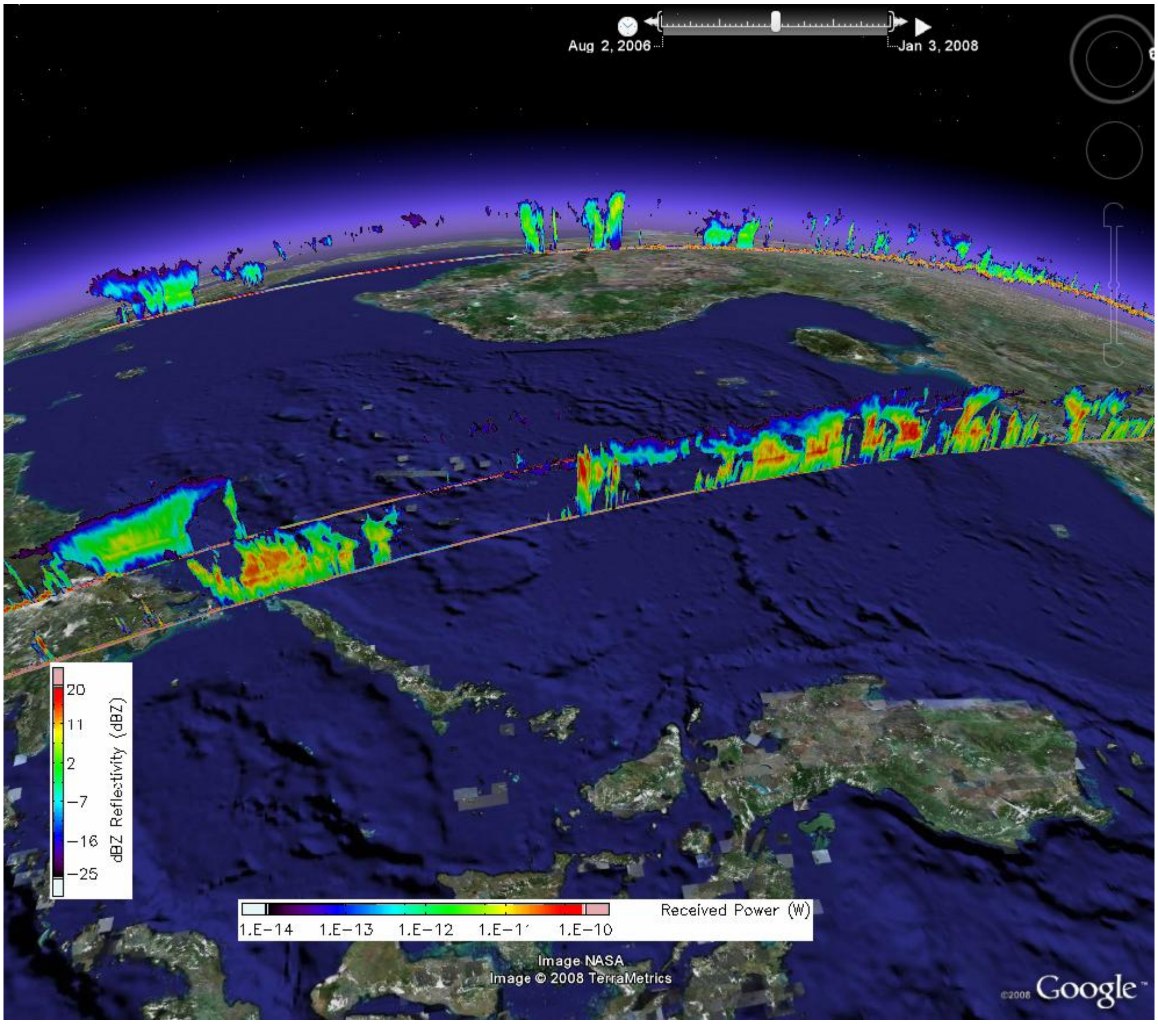


Figure 4 Synergy of vertical cloud data, aerosol data and atmospheric temperature data and horizontal surface strips respectively from CloudSat, CALIPSO and MODIS/Aqua of NASA A-Train constellation.

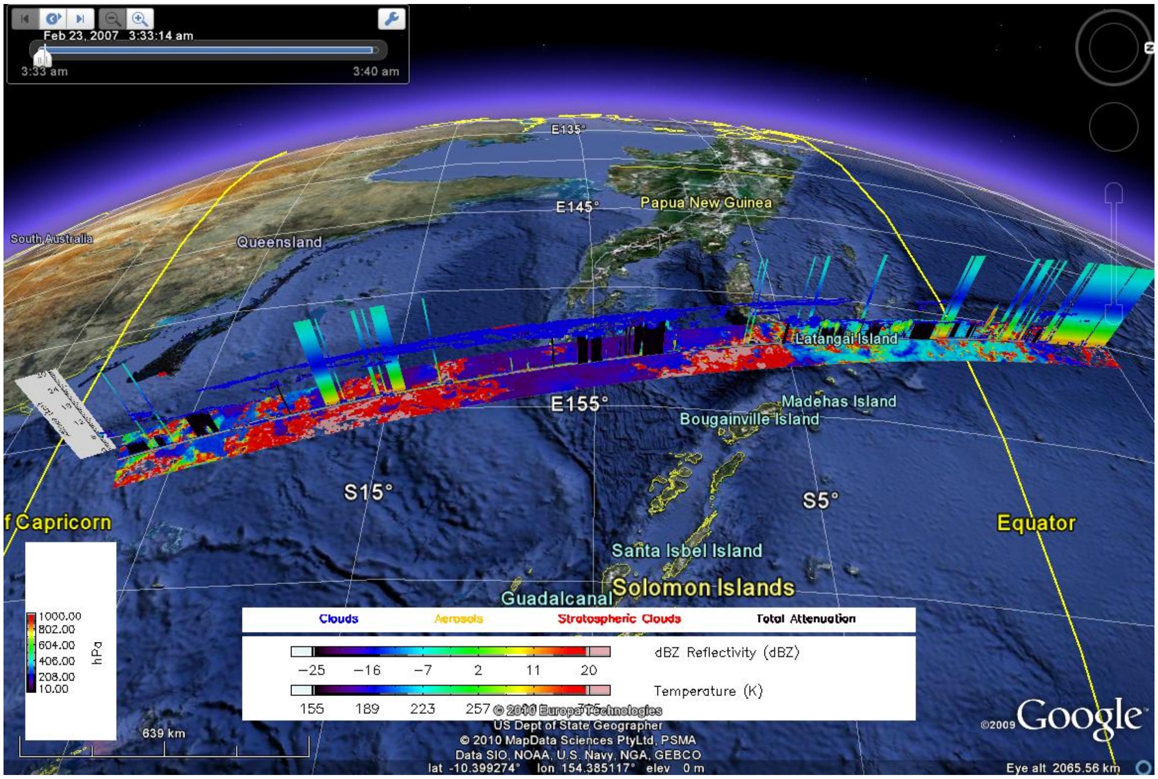


Figure 5 Synergy of vertical cloud data, and horizontal precipitation and wind data respectively from CloudSat, TRMM and QuikSCAT for typhoon Prapiroon on 2nd August, 2008 from TRMM in South China Sea.